Quasielastic (QE) e/ν Scattering and Two-Body Currents

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Outline:

- Nuclear interactions and electroweak currents: a review
- Role of two-body currents in inclusive e/ν scattering: the enhancement of the one-body response
- pn pairs in nuclei and the excess strength induced by two-body currents
- Summary

In collaboration with:

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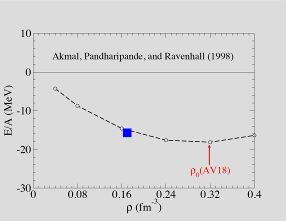
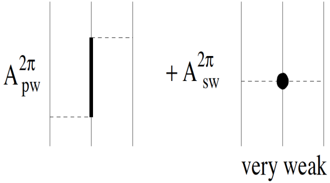
J. Carlson, S.C. Pieper, G. Shen, R.B. Wiringa

Nuclear interactions

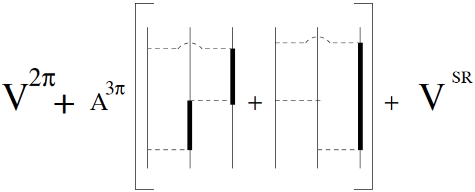




- $v = v_0(\text{static}) + v_p(\text{momentum dependent}) \rightarrow v(\text{OPE})$ fits large NN database with $\chi^2 \simeq 1$
- NN interactions alone fail to predict:
  - spectra of light nuclei
  - Nd scattering
  - nuclear matter $E_0(\rho)$
- 2π-NNN interactions

NNN interactions: beyond 2π-exchange

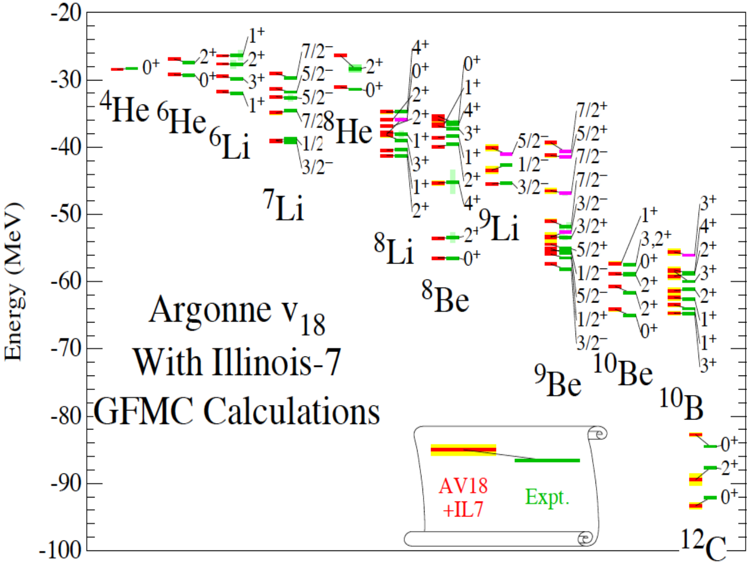
Pieper and Wiringa, private communication



- IL7 model: parameters (~ 4) fixed by a best fit to the energies of low-lying states (~ 17) of nuclei with $A \leq 10$
- AV18/IL7 Hamiltonian reproduces well:
  - spectra of A=9–12 nuclei (attraction provided by IL7 in $T = 3/2$ triplets crucial for p-shell nuclei)
  - low-lying p-wave resonances with J^π=3/2$^-$ and 1/2$^-$ as well as low-energy s-wave (1/2$^+$) scattering

Spectra of light nuclei

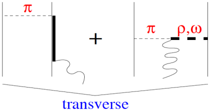
Pieper and Wiringa, private communication



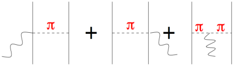
EM current operators I

Marcucci *et al.* (2005)

$\mathbf{j} = \mathbf{j}^{(1)}$

$+ \mathbf{j}^{(2)}(\mathrm{v}) +$ 

$+ \mathbf{j}^{(3)}(\mathrm{V}^{2\pi})$

$\mathbf{j}^{(2)}(\mathrm{v}) \xrightarrow[\text{long range}]{}$ 

- Static part v_0 of v from π-like (PS) and ρ-like (V) exchanges
- Currents from corresponding PS and V exchanges

$$\mathbf{j}_{ij}(v_0; PS) = \mathrm{i}\, G_E^V(Q^2)\, (\boldsymbol{\tau}_i \times \boldsymbol{\tau}_j)_z\, v_{PS}(k_j) \Big[\boldsymbol{\sigma}_i - \frac{\mathbf{k}_i - \mathbf{k}_j}{k_i^2 - k_j^2} \boldsymbol{\sigma}_i \cdot \mathbf{k}_i \Big] \boldsymbol{\sigma}_j \cdot \mathbf{k}_j + i \rightleftharpoons j$$

with $v_{PS}(k) = v^{\sigma\tau}(k) - 2\, v^{t\tau}(k)$ projected out from v_0

EM current operators II

- Currents from v_p via minimal substitution in i) explicit and ii) implicit p-dependence, the latter from

$$\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j = -1 + (1 + \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)\, \mathrm{e}^{\mathrm{i}(\mathbf{r}_{ji}\cdot\mathbf{p}_i + \mathbf{r}_{ij}\cdot\mathbf{p}_j)}$$

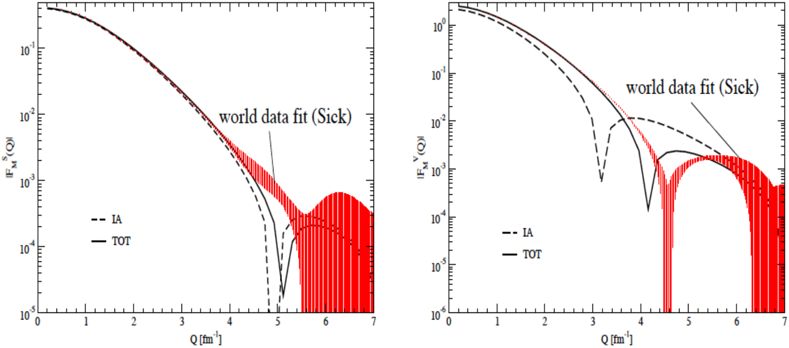
- Currents are conserved

$$\mathbf{q} \cdot \left[\mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V^{2\pi})\right] = \left[T + v + V^{2\pi}\,,\ \rho\right]$$

contain no free parameters, and are consistent with short-range behavior of v and $V^{2\pi}$, but are not unique

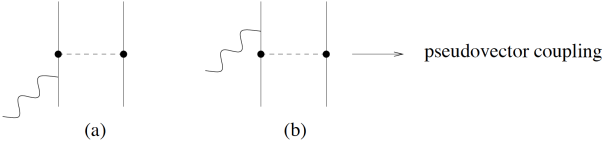
- EM current (and charge) operators also derived in χEFT up to one loop (Pastore *et al.* 2009-2013; Kölling *et al.* 2009-2011)

Isoscalar and isovector MFF of ^{3}He/^{3}H



- Isoscalar two-body current contributions small
- Leading isovector two-body currents from OPE

EM charge operators



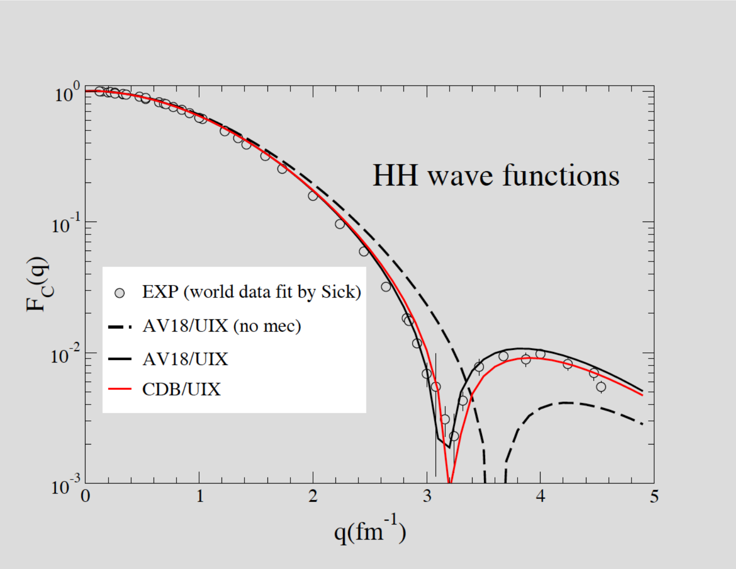
$$(\mathrm{a}) = v^{\pi}_{ij}\,\frac{1}{E_i - E}\,\frac{F_1^S + F_1^V \tau_{i,z}}{2} \to \text{included in IA}$$

$$-\frac{v_{PS}(k_j)}{2\,m}\,\boldsymbol{\sigma}_i \cdot \mathbf{q}\,\boldsymbol{\sigma}_j \cdot \mathbf{k}_j\,\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j\,\frac{F_1^S + F_1^V \tau_{i,z}}{2} + \mathcal{O}(E_i - E)$$

- Crucial for predicting the CFF's of ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Additional (small) contributions from vector exchanges as well as transition mechanisms like $\rho\pi\gamma$ and $\omega\pi\gamma$

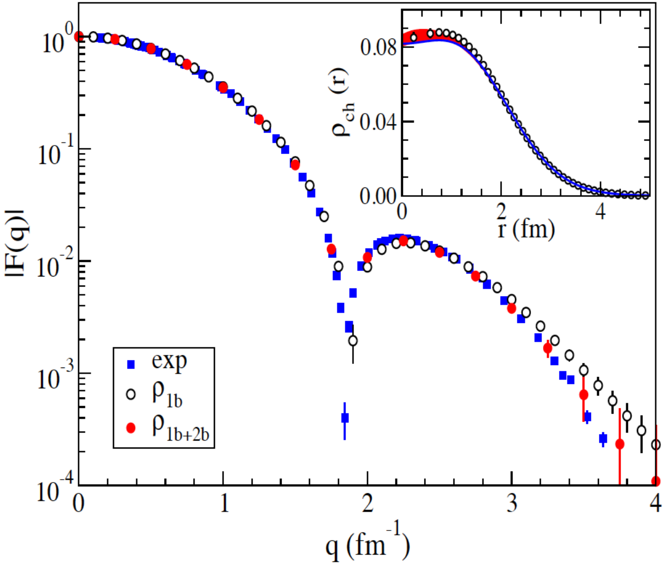
^{4}He CFF

Viviani *et al.* (2007)

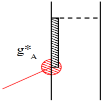


^{12}C CFF

Lovato *et al.* (2013)



Weak current operators



- Charge-changing (CC) and neutral (NC) weak currents (ignoring s-quark contributions)

$$j^{\mu}_{CC} = j^{\mu}_{\pm} + j^{\mu 5}_{\pm}$$

$$j^{\mu}_{NC} = -2\sin^2\theta_W\, j^{\mu}_{\gamma,S} + (1 - 2\sin^2\theta_W)\, j^{\mu}_{\gamma,z} + j^{\mu 5}_{z}$$

with $j_{\pm} = j_x \pm i\, j_y$ and the CVC constraint

$$\left[\, T_a \,,\, j^{\mu}_{\gamma,z} \,\right] = i\, \epsilon_{azb}\, j^{\mu}_{b}$$

- Contributions to two-body axial currents from π and ρ exchange, $\rho\pi$ transition, and Δ-excitation (g^*_A)
- Strategy: fix g^*_A (or $d_R(\Lambda)$ in χEFT) by fitting the GT m.e. in ^{3}H β-decay

Predictions for μ-capture rates on ^{2}H and ^{3}He

Marcucci *et al.* (2012–2013)

- Including radiative corrections [Czarnecki, Marciano, and Sirlin (2007)]

	$\Gamma_0(^3\text{He})$ s^{-1}
EXP	1496(4)
SNPA(AV18/UIX)	1496(8)
χEFT*(AV18/UIX)	
$\Lambda = 500$ MeV	1497(8)
$\Lambda = 600$ MeV	1498(9)
$\Lambda = 800$ MeV	1498(8)

- Chiral potentials (N3LO/N2LO) and currents lead *conservatively* to

$$\Gamma(^2\mathrm{H}) = 399(3)\ \mathrm{sec}^{-1} \qquad \Gamma(^3\mathrm{He}) = 1494(21)\ \mathrm{sec}^{-1}$$

- Studies of weak transitions in light nuclei in progress

Inclusive e/ν scattering

- Inclusive $\nu/\overline{\nu}$ $(-/+)$ cross section given in terms of five response functions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega} = \frac{G^2}{8\,\pi^2}\,\frac{k'}{\epsilon}\left[v_{00}\,R_{00}+v_{zz}\,R_{zz}-v_{0z}\,R_{0z}+v_{xx}\,R_{xx}\mp v_{xy}\,R_{xy}\right]$$

$$R_{\alpha\beta}(q,\omega)\sim\overline{\sum_i}\sum_f \delta(\omega+m_A-E_f)\langle f\,|\,j^\alpha(\mathbf{q},\omega)\,|i\rangle^*\langle f\,|\,j^\beta(\mathbf{q},\omega)\,|i\rangle$$

- In (e,e') scattering, interference $R_{xy}=0$, $j^z_\gamma\sim(\omega/q)j^0_\gamma$, and only $R_{00}=R_L$ and $R_{xx}=R_T$ are left
- Theoretical analysis via:
  - sum rules
  - explicit calculations of $R_{\alpha\beta}$

Ab initio approaches to inclusive scattering (IS)

Response functions require knowledge of continuum states: hard to calculate for $A \geq 3$

- Sum rules: integral properties of response functions
- Integral transform techniques

$$E(q,\tau) = \int_0^\infty \mathrm{d}\omega \, K(\tau,\omega) \, R(q,\omega)$$

  and suitable choice of kernels (i.e., Laplace or Lorentz) allows use of closure over $|f\rangle$
- While in principle exact, both these approaches have drawbacks

Sum rules

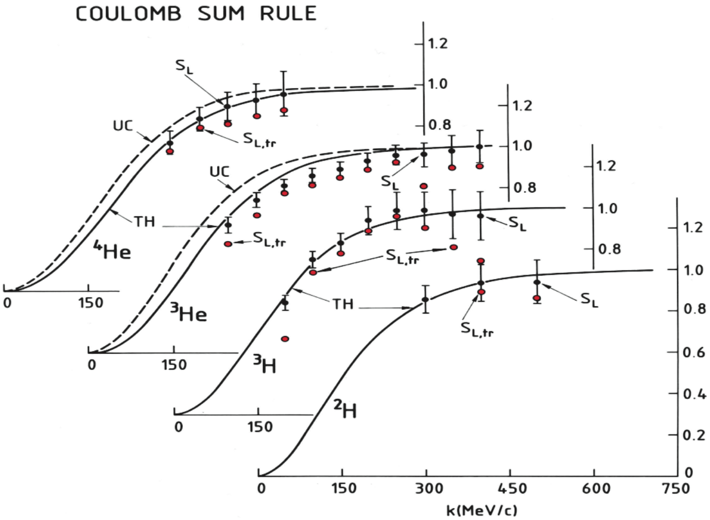
Schiavilla *et al.* (1989); Carlson *et al.* (2002–2003)

$$\begin{aligned} S_\alpha(q) &= C_\alpha \int_{\omega_{\rm th}^+}^{\infty} \mathrm{d}\omega \, \frac{R_\alpha(q,\omega)}{G_{Ep}^2(q,\omega)} \\ &= C_\alpha \left[\langle 0 | \, O_\alpha^\dagger(\mathbf{q}) \, O_\alpha(\mathbf{q}) \, | 0 \rangle - | \, \langle 0 | \, O_\alpha(\mathbf{q}) \, | 0 \rangle \, |^2 \right] \end{aligned}$$

- C_α are normalization factors so as $S_\alpha(q \to \infty) = 1$ when only one-body terms are retained in O_α
- Direct comparison between theory and experiment for inclusive (e, e') problematic:
  - $R_\alpha(q, \omega)$ measured by (e, e') up to $\omega_{\rm max} \le q$
  - present theory ignores explicit pion production mechanisms, crucial in the Δ-peak region of R_T

Coulomb sum rule $A = 2$–4 nuclei

Schiavilla *et al.* (1989,1993)

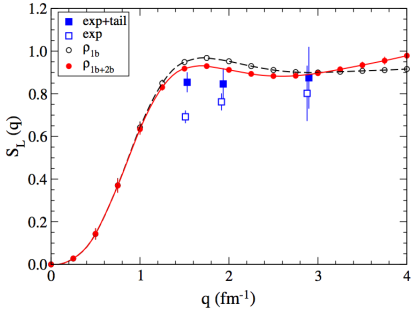


Coulomb sum rule in ^{12}C

Lovato *et al.* (2013)

- Theory and experiment in reasonable agreement; new JLab data on ^{12}C forthcoming ...
- Contribution for $\omega > \omega_{\rm max}$ estimated by assuming

$$R_L(q, \omega > \omega_{\rm max}; A) \propto R_L(q, \omega; \text{deuteron})$$

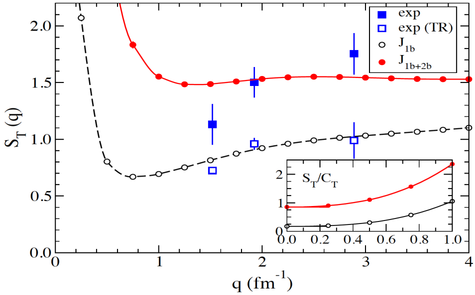


EM transverse sum rule in ^{12}C

Lovato *et al.* (2013)

- Large contribution from two-body currents
- Comparison with experiment problematic
- Small q divergence due to choice of normalization

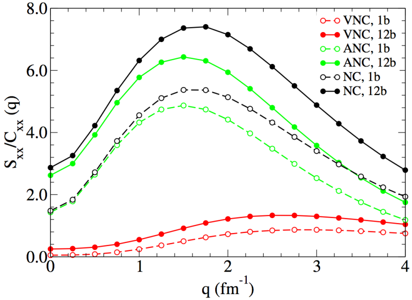
$$C_T = \frac{2}{Z\,\mu_p^2 + N\,\mu_n^2}\,\frac{m^2}{q^2}$$



Weak NC $S_{xx}(q)$ (transverse) sum rule in ^{12}C

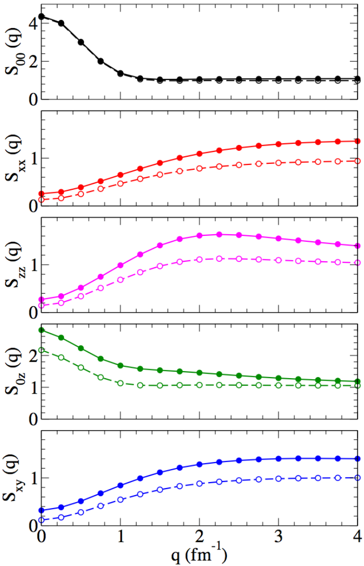
Lovato *et al.* (2014)

$$S_{xx}(q) = C_{xx} \int_{\omega_{\rm el}}^{\infty} {\rm d}\omega\, R_{xx}(q,\omega) = C_{xx} \langle 0 | \mathbf{j}^{\perp\,\dagger}_{NC}(\mathbf{q})\, \mathbf{j}^{\perp}_{NC}(\mathbf{q}) | 0 \rangle$$



- Large increase ($\sim 30\%$) in the weak NC transverse response R_{xx} due to two-body (2b) currents
- Important interference effects in $S_{\alpha\beta}$ between 1b and 2b (as well as among 2b) terms

Weak NC sum rules in ^{12}C



Response functions

Carlson and Schiavilla (1992,1994)

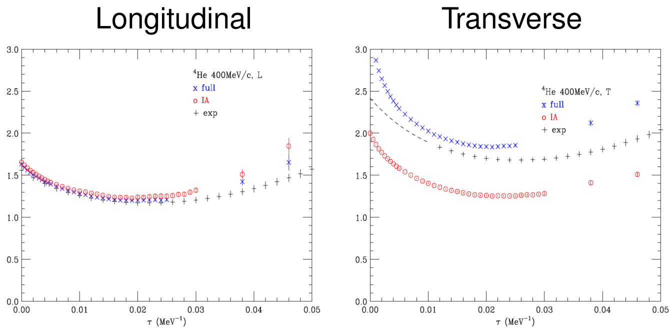
- Direct calculation in ^{2}H; calculation of Euclidean response functions in $A \geq 3$

$$
\begin{aligned}
\widetilde{E}_\alpha(q,\tau) &= \int_{\omega_{\rm th}^+}^\infty d\omega\, e^{-\tau(\omega-E_0)} \frac{R_\alpha(q,\omega)}{G_{Ep}^2(q,\omega)} \\
&= \langle 0 |\, O_\alpha^\dagger(\mathbf{q}) e^{-\tau(H-E_0)} O_\alpha(\mathbf{q})\, | 0 \rangle - (\text{elastic term})
\end{aligned}
$$

- $e^{-\tau(H-E_0)}$ evaluated stochastically with QMC
- At $\tau = 0$, $\widetilde{E}_\alpha(q;0) \propto S_\alpha(q)$; as τ increases, $\widetilde{E}_\alpha(q;\tau)$ is more and more sensitive to strength in QE region
- Inversion of $\widetilde{E}_\alpha(q;\tau)$ difficult; in EM case, Laplace transform data instead

EM euclidean response functions in ^{4}He

Carlson *et al.* (2002)



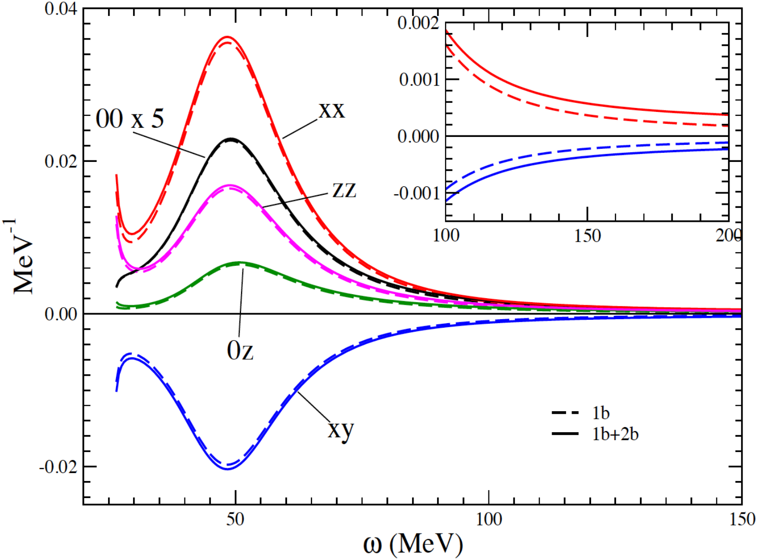
$$E_\alpha(q,\tau) = \exp\left[\tau\, q^2/(2\,m)\right]\; \widetilde{E}_\alpha(q,\tau)$$

and $E_L(q,\tau) \to Z$ for a collection of protons initially at rest

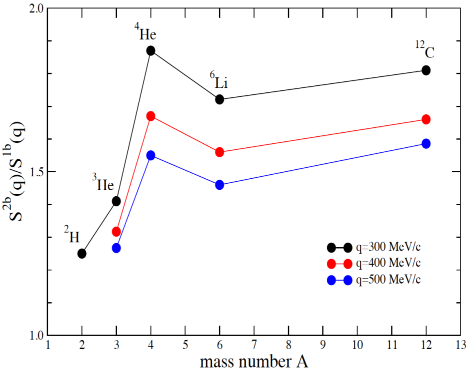
- The $\tau \gtrsim 0.01$ MeV^{-1}region sensitive to QE strength
- Large enhancement of R_T in QE region

Weak NC response functions in ^{2}H

Lovato *et al.* (2014)



Excess strength systematics in EM R_T



- A-dependence of $\Delta S_T = S_T - S_T^{1b}$

A-systematics of ΔS_T

Carlson *et al.* (2002)

$$\Delta S_T \propto \langle 0 | \sum_{l<m} \left[(j_l^\dagger + j_m^\dagger) j_{lm} + \text{h.c.} \right] + \sum_{l<m} j_{lm}^\dagger j_{lm} + \cdots | 0 \rangle$$

- Neglecting 3- and 4-body terms

$$\Delta S_T{}^A(q) \simeq C_T \int_0^\infty \mathrm{d}x \, \mathrm{tr} \left[F(x;q)\, \rho^A(x;pn) \right]_{\sigma\tau} = \int_0^\infty \mathrm{d}x \, I^A(x)$$

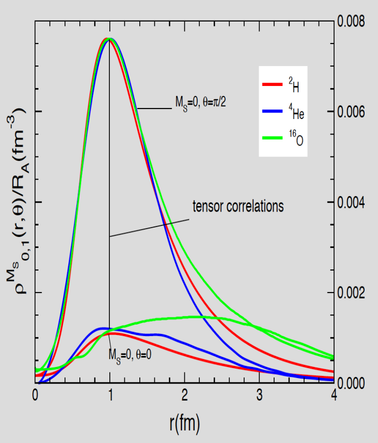
- Scaling property $\rho^A(x;pn,T=0) \simeq R_A \, \rho^d(x)$ and similarly for $T=1$ pn pairs with $\rho^d \longrightarrow \rho^{qb}$; hence

$$I^A(x) \text{ scales as } \frac{R_A}{Z\,\mu_p^2 + N\,\mu_n^2}$$

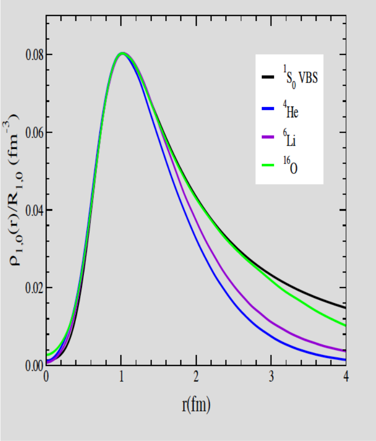
Scaling of pair densities in nuclei

Forest *et al.* (1996)

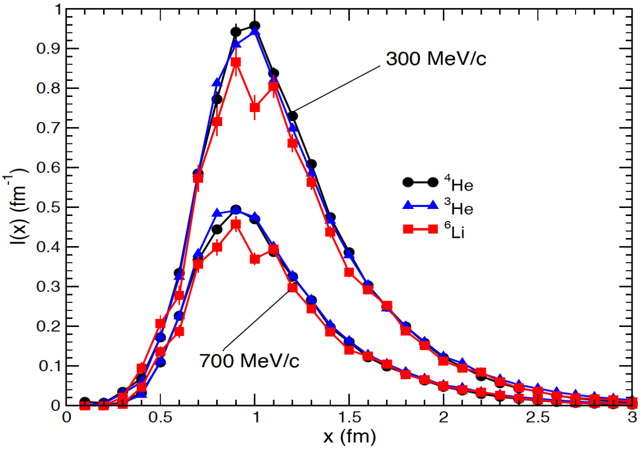
TS=01 (d-like)



TS=01 (quasi-bound)



A-scaling property of ΔS_T



After rescaling by $R_A / \left(Z\, \mu_p^2 + N\, \mu_n^2 \right)$, the integrand $I^A(x)$ is about the same in all nuclei

np and pp momentum distributions in nuclei

Wiringa *et al.* (2014)

QE e/ν Scattering

Nuclear interactions

Nuclear currents

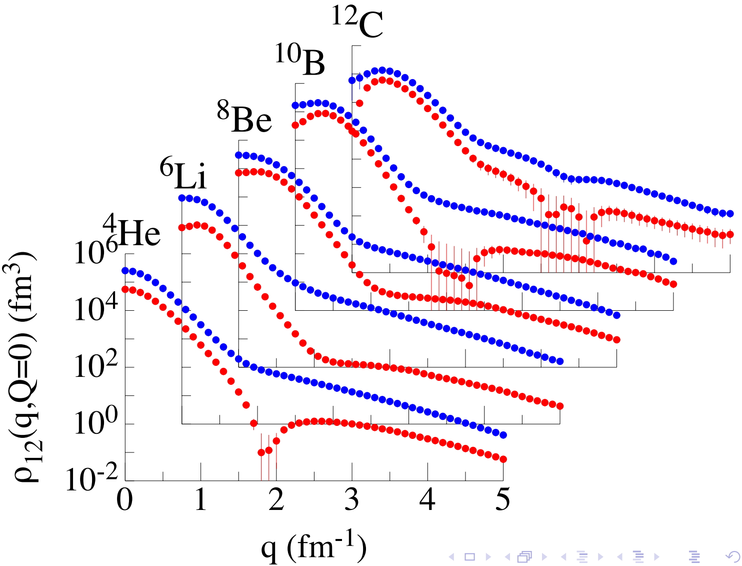
e/ν scattering

Sum rules

Response functions

Role of pn correlations

Summary



Summary

- Large enhancement due to two-body currents in sum rules of electroweak response functions
- There is a direct link between this enhancement and the short-range structure of pn pairs in nuclei
- This short-range structure also drives the increase of the one-body response due to two-body currents
- Calculations of EM transverse response in ^{4}He show an excess strength as large as $\sim 30\%$ in QE region
- Calculations of NC (and CC) Euclidean response functions in ^{12}C are in progress